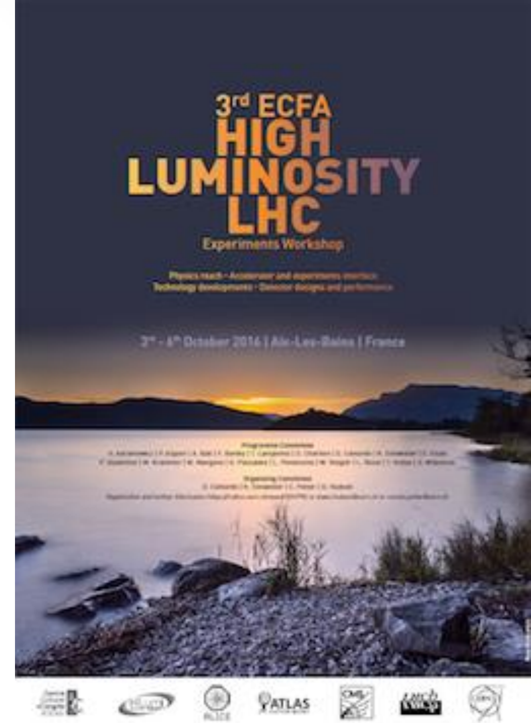
Updated Projections for BSM Studies

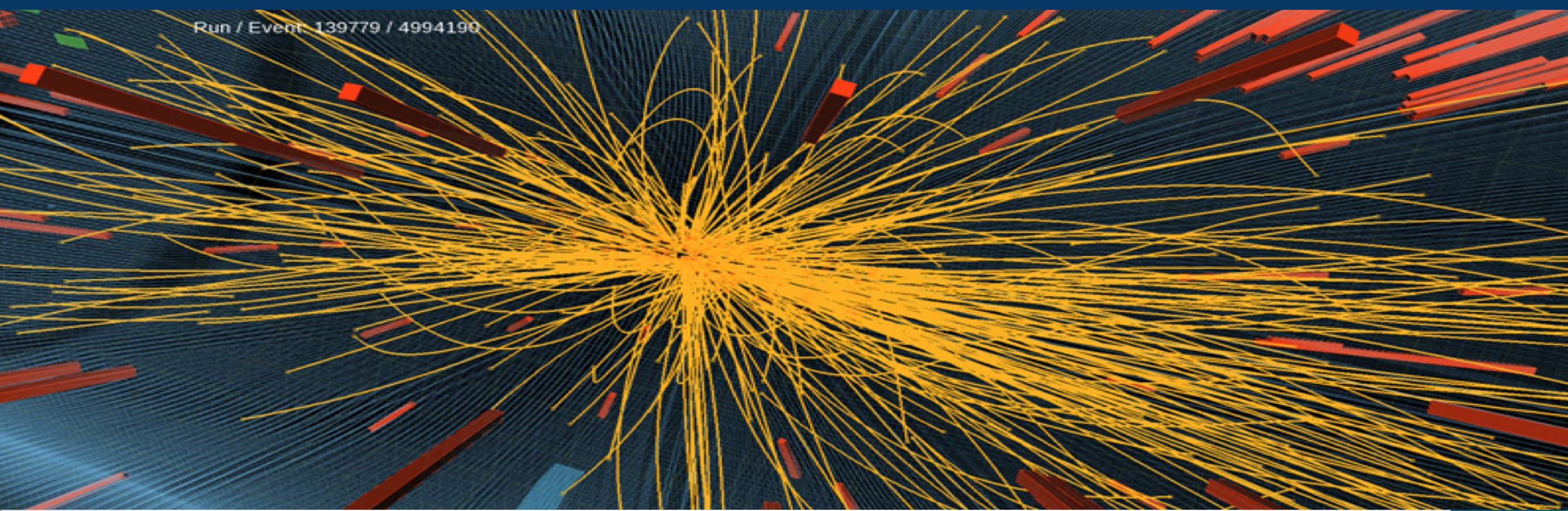
ECFA 2016

Kerstin Hoepfner (RWTH Aachen)

on behalf of the ATLAS, CMS and LHCb collaborations

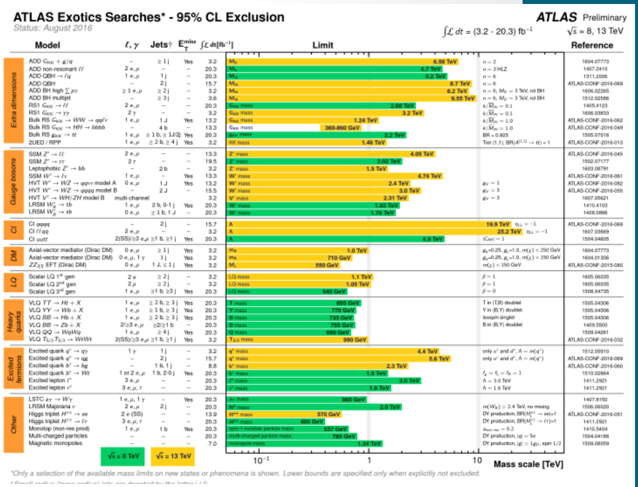


ECFA HL-LHC Workshop October 4th 2016



Motivation

LHC is a **discovery machine**. Many ongoing searches... Indications here and there but no conclusive sign of new physics yet. Try not to leave any stone unturned.



BSM searches at HL not a linear extrapolation from presence. Rather **widen the scope**, e.g.:

- Rare processes, weaker couplings
- New models upcoming including observed LHC results
- Go more model-independent not to miss something

How to prepare for phase-II physics?

→ Continue benchmark analyses

→ Develop new analysis strategies

SCOPE of this talk: show selected examples

Background information about upgraded detectors and their performance given in experimental talks.

Details in Monday talks about detector upgrade programs

Selected new results@ECFA2016

Hitoshi Murayama

- New heavy particles
- Dark matter (DM)
- Supersymmetry
- Long-lived particles (LLP)

Analysis Technique for ATLAS

Truth + Smear technique

More details in Higgs talk by Victoria Martin this morning

- **Generate truth-only** 14 TeV event
- Overlay with jets (full sim) from pileup library, <PU> = 140 or 200
- Reconstruct particles (electrons, muons, jets, MET) from truth+overlay
- Smear their energy and p_T using **appropriate smearing functions,** incl. efficiencies for genuine objects and rates from mis-identified objects.
  - Depending on p_T and eta
  - Functions are based on fully simulated samples for upgraded ATLAS detector and high PU conditions
  - Approach validated on some analyses
- Apply efficiencies for trigger and object reconstruction

Analysis Techniques for CMS

Two methods – either projection from present or parametrized simulation

→ Projections from a present analysis

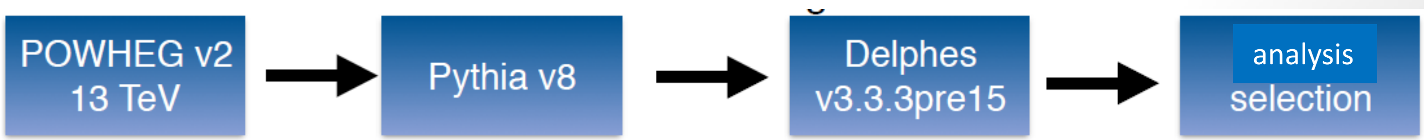
- Existing signal and background samples (simulated at 13 TeV) scaled to higher luminosity and sqrt(s)=14 TeV.
- Analysis steps (cuts) from present analyses.
- Three scenarios for systematics:
  - (1) keep present systematics (2) Improved by a fixed factor (3) no systematics, only statistics

See talk by Meenakshi Narain Monday morning

→ Full analysis with parametrized detector performance

- DELPHES with up-to-date phase-2 detector performance (tracking, vertexing, timing, dedicated PUPPI jet algorithms, increased acceptance, performance of new detectors)
- Consider <PU> = 200
- Analysis steps (cuts) guided by present analysis. Limited optimization for HL conditions. Cross checks with present analysis.
- Dedicated simulation of signal and bkgr samples

Example:



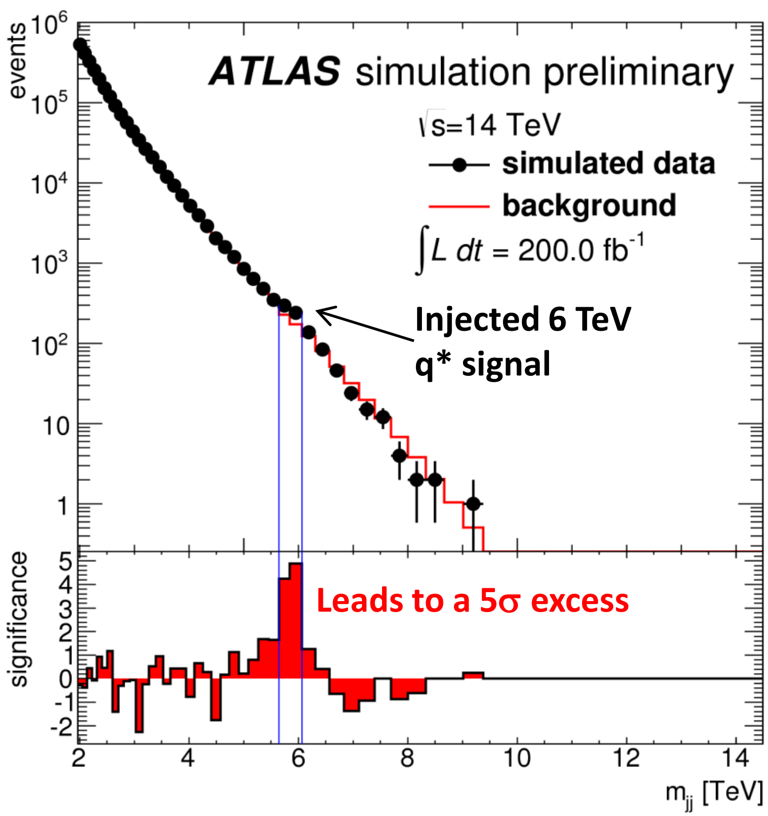
Benchmark Analyses: Search for New Particles

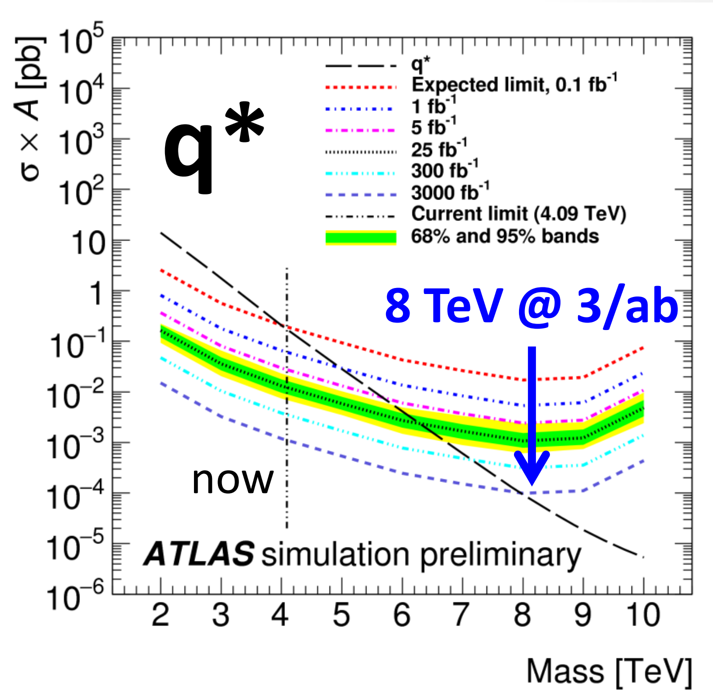
ATLAS Dijet (bump hunt)

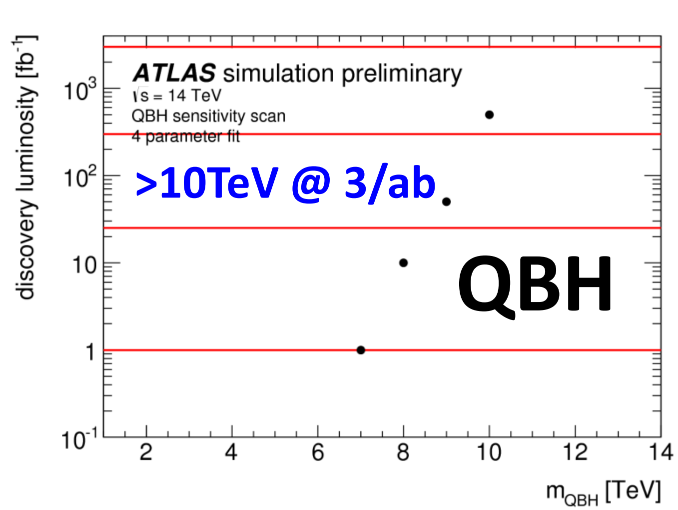
Discovery reach for excited quarks (q*) and quantum black holes (QBH)

Powerful search technique for new physics, **model-independent** as long as a sharp resonance. Many interpretations possible.

Bump-hunter algorithm (Similar technique for other analyses such as CMS Z′ and ATLAS HH to 4b)

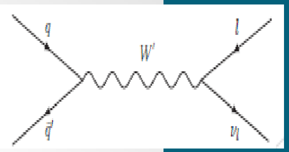






ATL-PHYS-PUB-2015-004

W´ Projected Discovery Reach

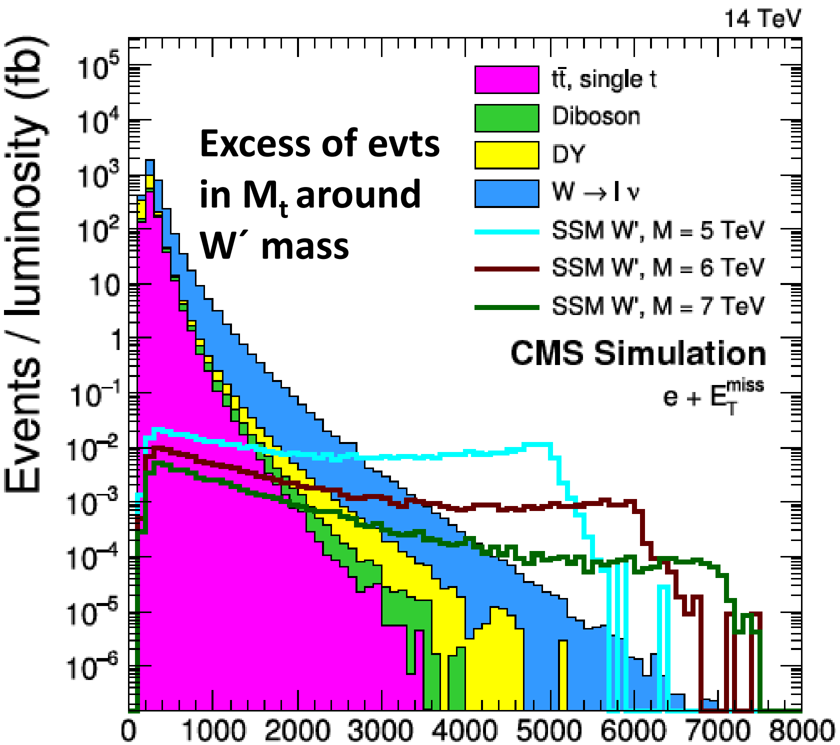


Benchmark analysis with max discovery sensitivity. Full DELPHES analysis.

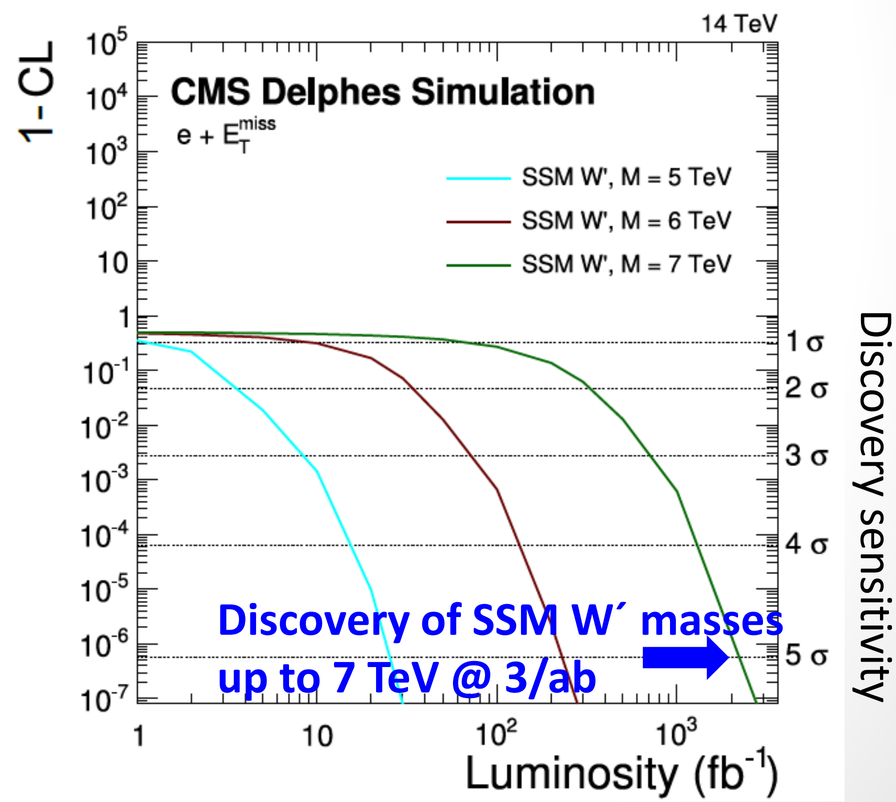
Electron channel with good **resolution at very high mass** and rather flat resolution. Discriminating variable = M_t from (e, MET)

Key: understand the M_t tail and performance of high p_T leptons.

Assume systematics from run-2.



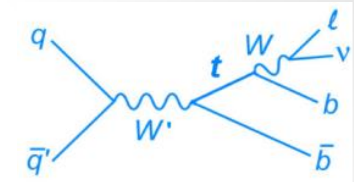
$$M_T = \sqrt{2 p_T^l E_T^{miss} (1 - \cos[\Delta\phi(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss})]}$$



CMS-PAS-EXO-14-007

W′→tb Impact of Systematics

Projection of exclusion limit



Probe scenarios such m(ν_R) > m(W′) → forbidden for W′→lν

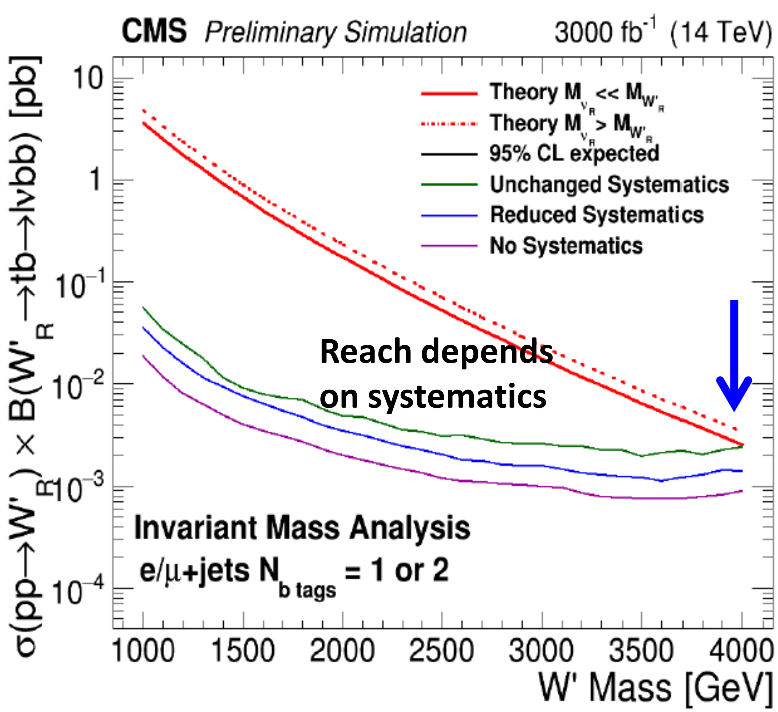
Two scenarios to extrapolate systematics from 12.9/fb to 3/ab

1) Leave **systematics unchanged**, simply scale templates with lumi
2) **Reduce** most experimental to percent level, theo uncertainties by factor 2, top p_T reweighting by factor 3

→Impact on projected exclusion limit: 4(4.2) TeV for case 1(2)

Source	Rate Uncertainty (Flat)	Rate Uncertainty (Scaled)
Luminosity	6.2%	1.5%
Trigger Efficiency (e/μ)	2%/5%	1%/1%
Lepton ID Efficiency (e/μ)	5%/2%	1%/1%
Jet Energy Scale	3.8%	1%
Jet Energy Resolution	1%	0.07%
b/c-tagging	2.7%	1%
light quark mis-tagging	1.2%	1.2%
W+jets Heavy Flavor Fraction	2.3%	1.1%
Top p_T Reweighting	18%	6%
Pileup	1.3%	0.09%
PDF	6.1%	3%
Matrix element Q^2 scale	18.9%	9.5%
$t\bar{t}$ Parton matching Q^2 scale	1.7%	0.9%
Top cross section	15%	7.5%
Bosonic cross section	10%	5%

Theoretical uncertainties comparable to experimental



Exclusion limit m(W′) >4 TeV @3/ab

Baseline analysis tb at 13 TeV B2G-15-004, B2G-16-017.
Projection in DP-2016/064

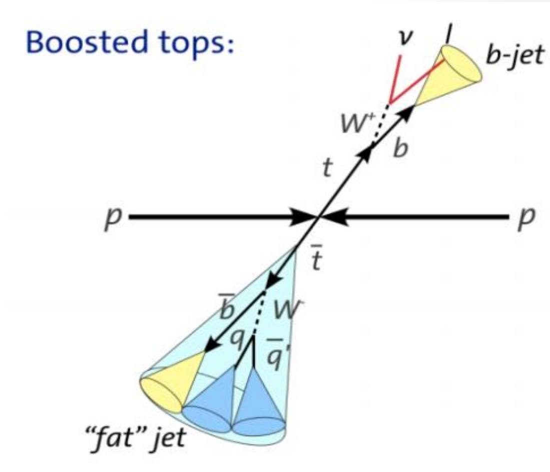
Z′→tt Projection from 2.6/fb to 3/ab

Projection of exclusion limit

Z′→ttbar studied in two dinstinct channels distinguished by decay of W (from t→Wb)

- Semileptonic (l + b-jet + jet + MET)
- All-hadronic channel (jets)

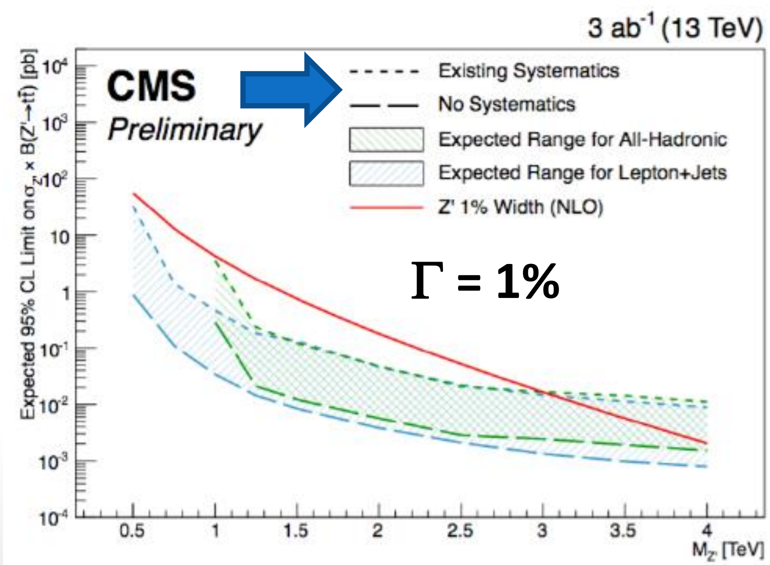
12 orthogonal categories

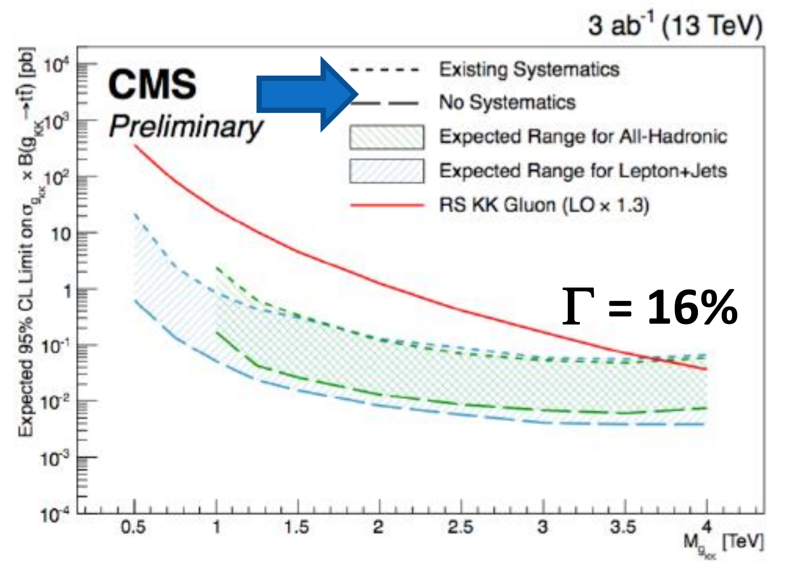


Scenarios for systematic uncertainties:

(1) Leave **systematics unchanged**

(2) No systematic uncertainties applied – „**performance limit**“ of analysis





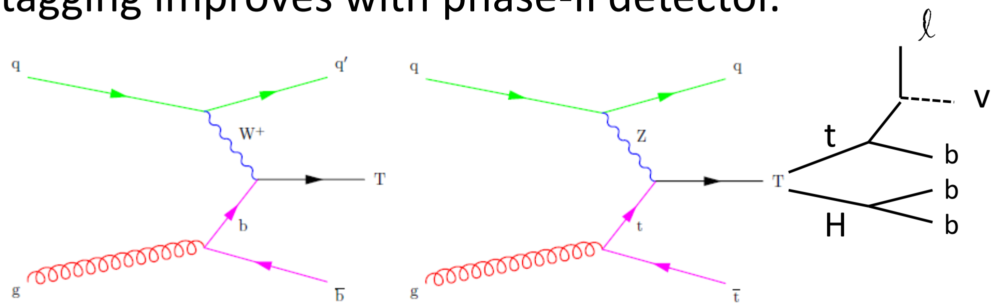
Exclusion limit O(4 TeV) depending on resonance width and systematics

Baseline analyses at 13 TeV B2G-15-002, B2G-15-003.
Projection in DP-2016/064

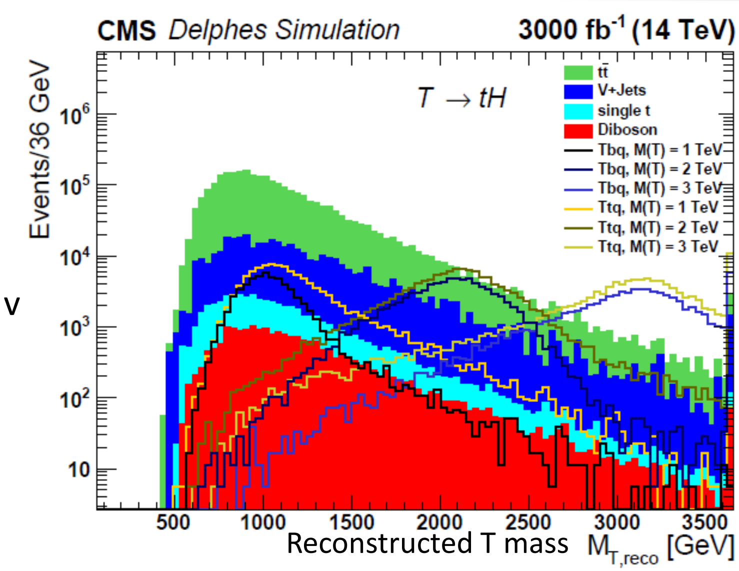
EWK Production of Single VLQ

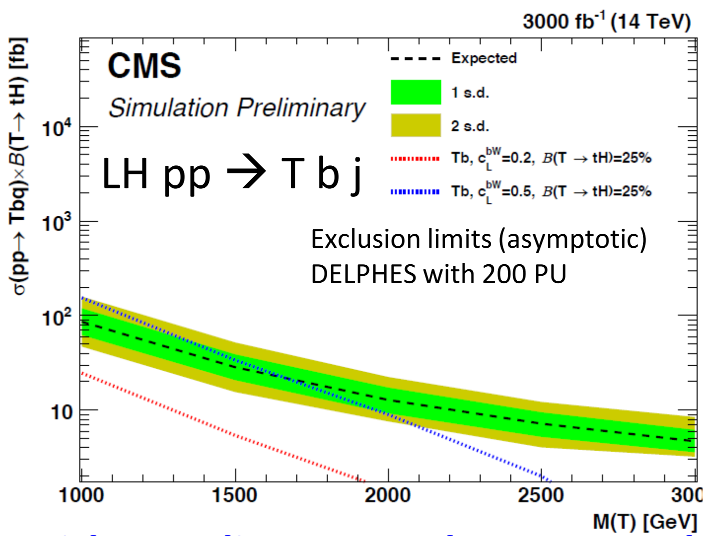
Vector-like quark (VLQ) decay via T→tH

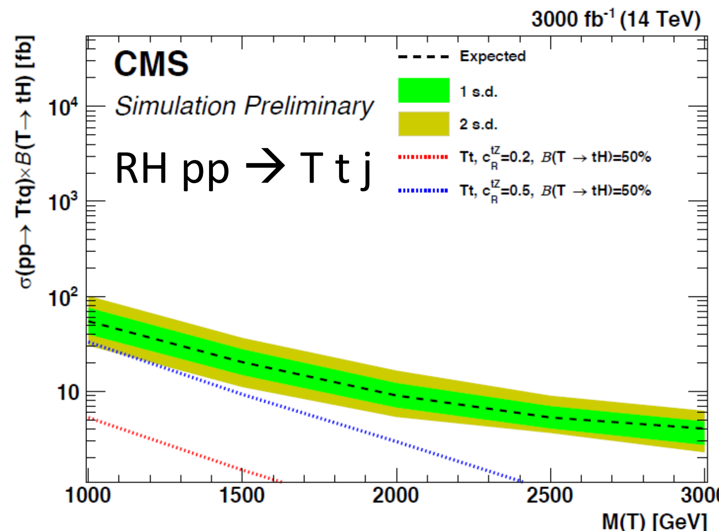
Event signature has a very forward jet that can benefit from forward upgrade . Also b-tagging improves with phase-II detector.



Full analysis with DELPHES



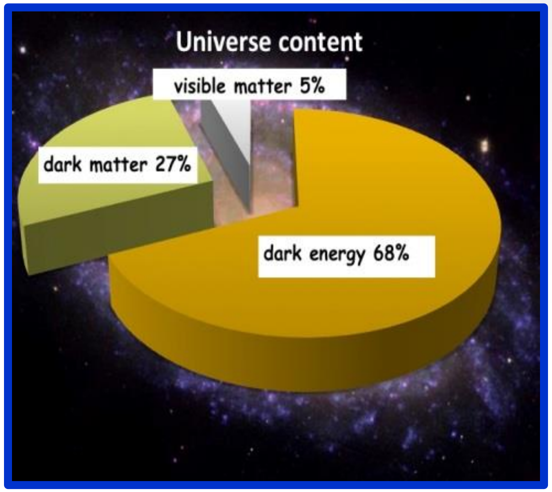




With coupling strength c = 0.5 exclusion reach M(T)>1.6 TeV (LH) @3/ab.
For weaker couplings more luminosity is needed.

Baseline analyis CMS-PAS-B2G-15-008.
HL analysis in DP-2016/064

Dark matter Next discovery?



Many indications for existence of dark matter (DM) but **what is its nature**?

LHC searches **complement** direct detection experiments.
Very **dynamic** topic. In recent years significant theoretical and experimental developments, e.g. EFT→simplified models.

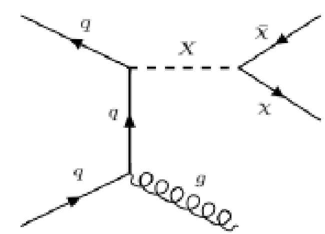
Classical jet + MET DM Channel

Suppressed in direct detection. LHC provides complementary sensitivity for AV. Full analysis in DELPHES.

Benchmark among many DM collider searches. Interpretation in **simplified model** following LHC DM forum (arXiv: 1507.00996) with

4 parameters ($\mathbf{M_{med}}$, $\mathbf{m_{DM}}$, g_{SM}, g_{DM})

2D exclusion limit



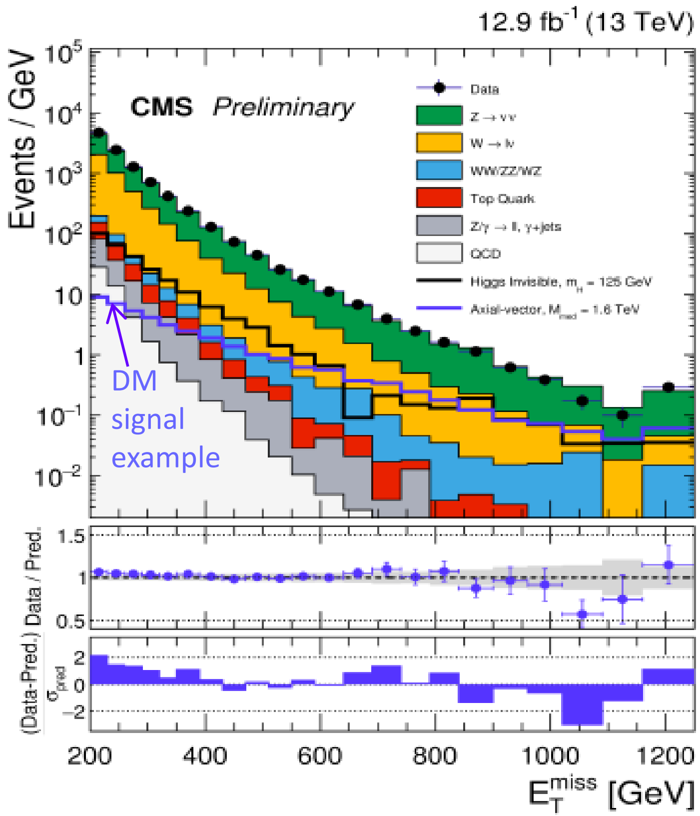
Spin-1 mediator, axialvector

$g_{SM} = 0.25$, $g_{DM} = 1$

Final state: large MET (>200 GeV) ($\chi\bar{\chi}$) + jet

Main bkgr: 70% Z(vv)+j ; 30% W(lv)+j

→ data-driven using muons Z(μμ), W(μv)



Analysis procedure

Bin MET distribution in 22 exclusive bins.

At HL-LHC extend to MET > 2.4 TeV (now 1.2 TeV).

Baseline analzsis PAS-EXO-16-037.
Projection in DP-2016/064

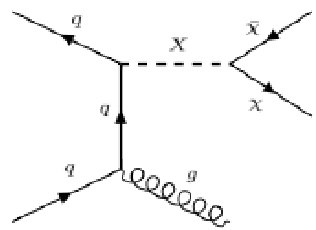
Classical MET+jet - Axialvector

Suppressed in direct detection. LHC provides complementary sensitivity. Full analysis in DELPHES.

Benchmark among many DM collider searches. Interpretation in **simplified models** following LHC DM forum (arXiv: 1507.00996) with

4 parameters (**M_{med}, m_{DM}**, g_{SM}, g_{DM})

2D exclusion limit

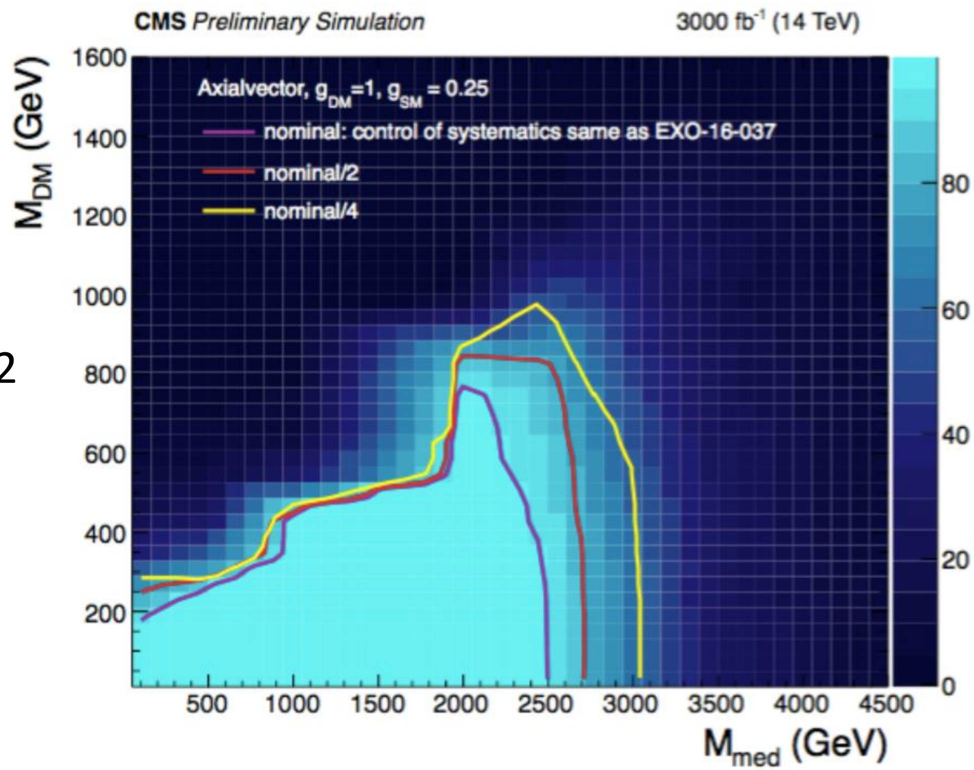


Spin-1 mediator, axialvector
$g_{SM} = 0.25$, $g_{DM} = 1$

Reach in mediator mass influenced by systematics. First shown in ATL-PHYS-PUB-2014-007 (EFT approach).

Maximum reach **3 TeV @ 3/ab** if Run-2 systematics (EXO-16-037) is achieved.

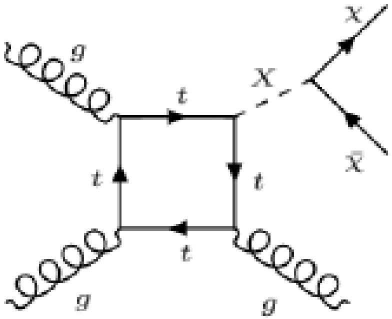
Dominating systematics = understanding MET tails as one needs to go to higher MET.



Baseline analzsis PAS-EXO-16-037.
Projection in DP-2016/064

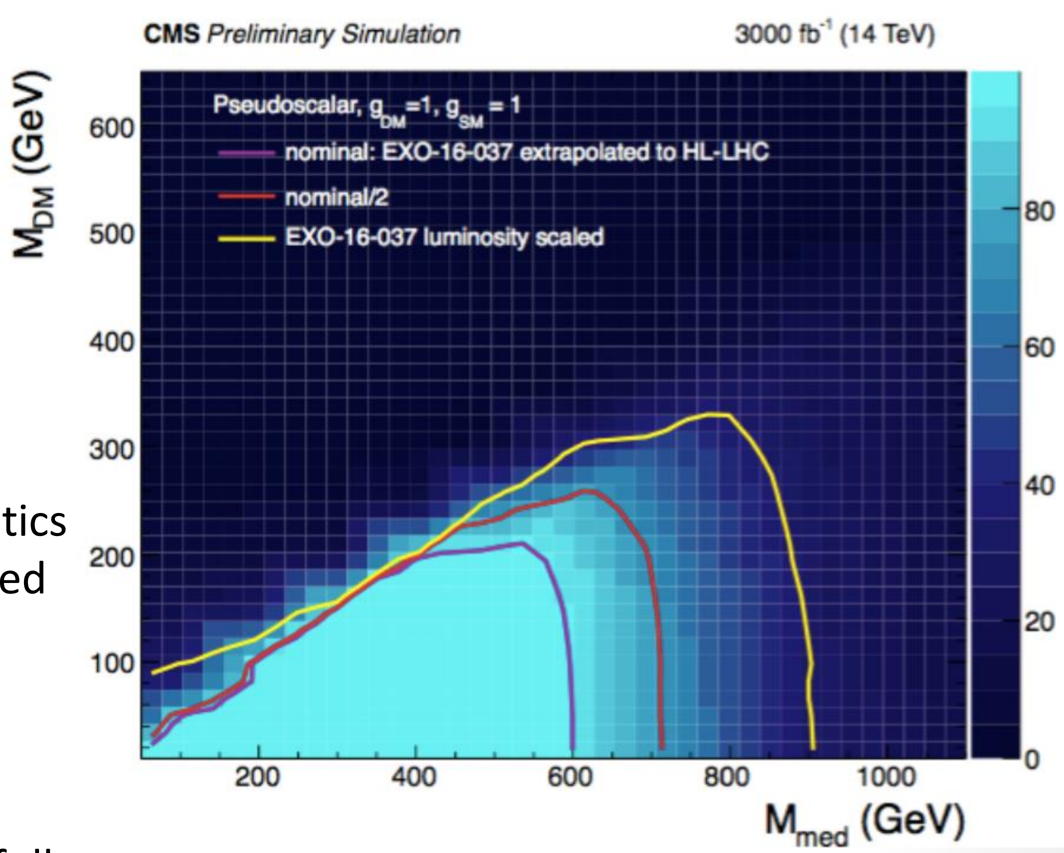
MET+jet DM – Pseudoscalar

Not accessible to direct detection. Only LHC provides sensitivity.



Spin-0 mediator, pseudoscalar

g_{SM} = 1, g_{DM} = 1



Systematics scenarios:

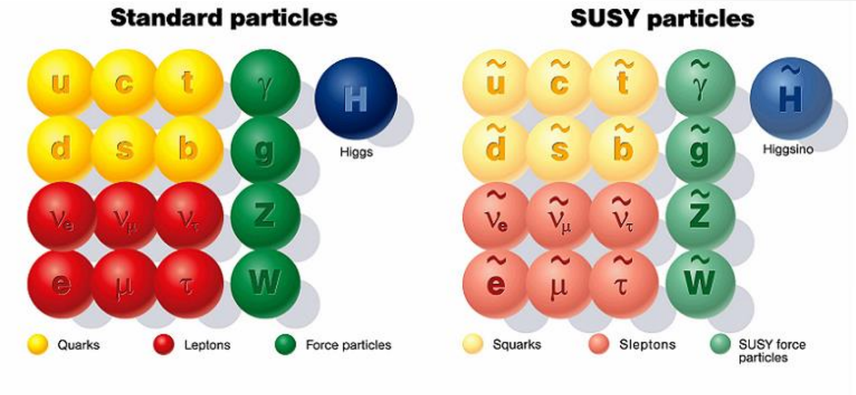
(1) Nominal = scale run-2 systematics at low MET which are dominated by lepton ID/ISO to HL-LHC recommendation, high MET dominated by statistics.

(2) Nominal divided by 2

(3) Scale run-2 systematics in the full MET range by luminosity

Baseline analzsis PAS-EXO-16-037.
Projection in DP-2016/064

Searches for Super-symmetry



Search for SUSY one of the main LHC goals.

For HL, other SUSY models move into focus.

- Study properties if new particle(s) discovered
- Turn to low cross sections and compressed mass spectra
- Special signatures such as heavily ionizing and long-lived particles

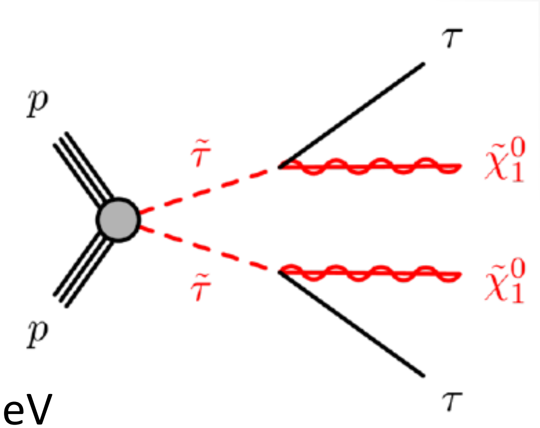
Direct Production of stau Pairs

Assume 100% BR to SM tau and LSP.

Signature:

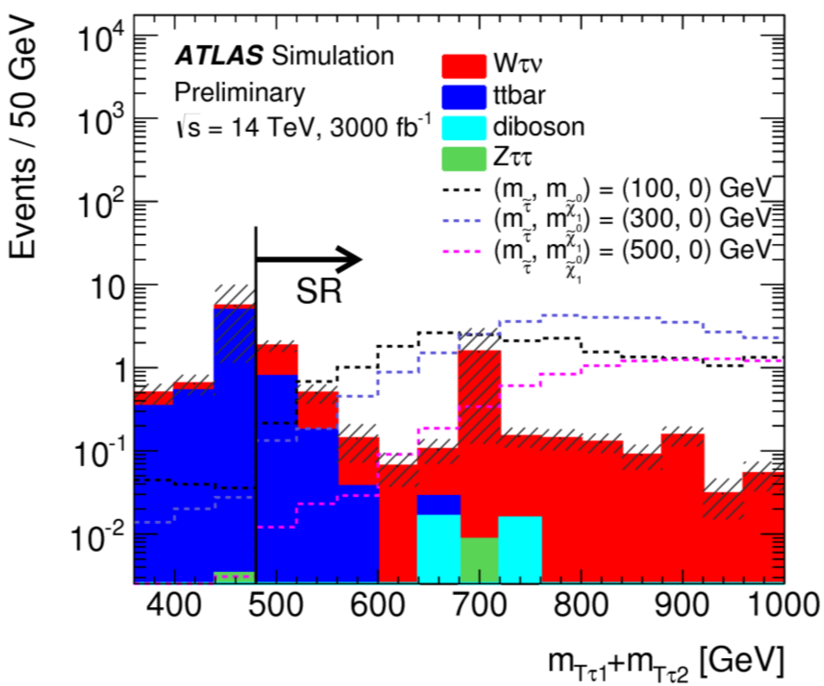
- 2 tau jets (hadronically decaying tau)
- Large MET (from $\tilde{\chi}_1^0$)

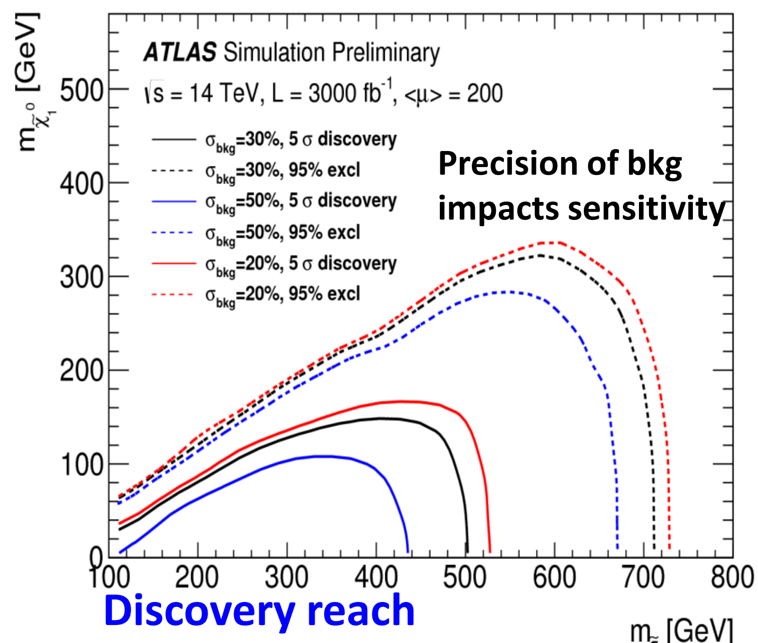
Main background: W+jets, ttbar



Selection: 2 OS taus, loose jet and Z-veto, MET>280 GeV

Define signal region (SR) in $m_T(\tau 1) + m_T(\tau 2)$





Discovery reach

430-520 GeV @ 3/ab depending on bkg

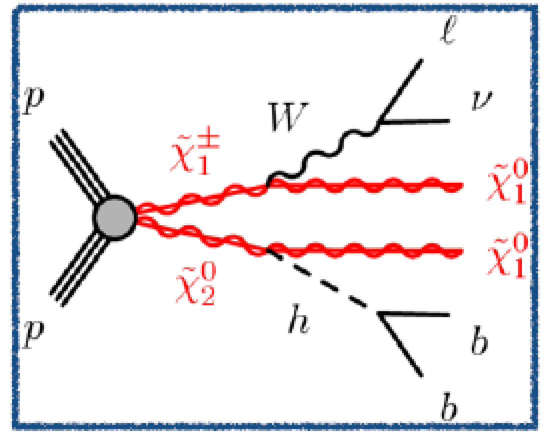
ATL-PHYS-PUB-2016-021

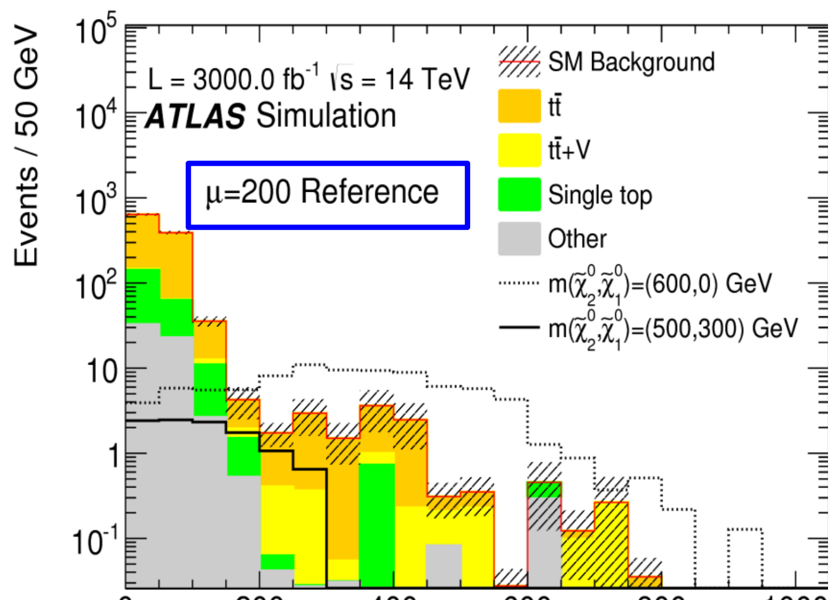
Direct Production of Chargino $(\tilde{\chi}^{\pm})$ and Neutralino $(\tilde{\chi}^{0})$ decaying to Wh

Signature:

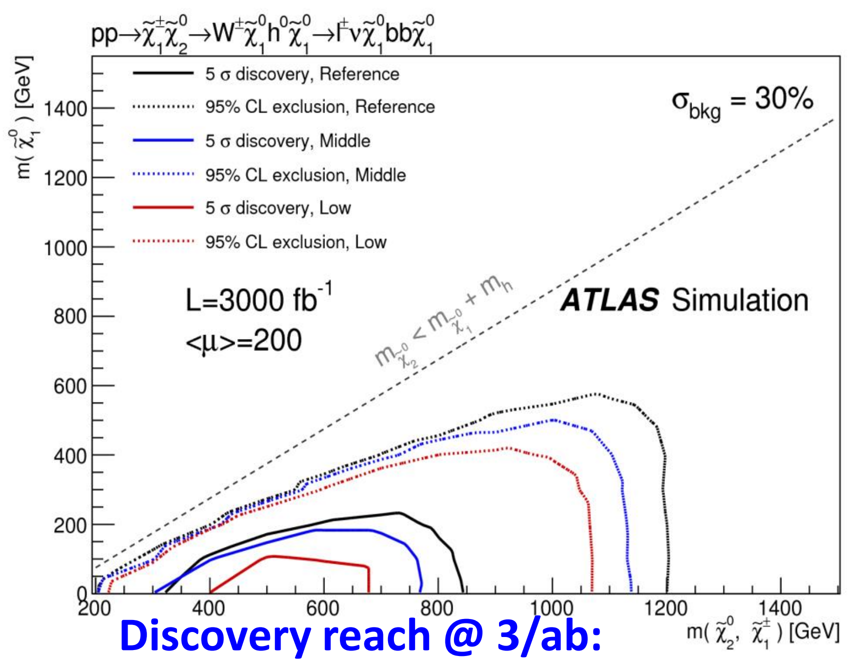
- Chargino to W (leptonic) = clear signature
- Neutralino to h(bb) = large impact of upgraded detector design
- Large MET

Main background: W+jets, ttbar, single t, ttV





Discriminating variable: transverse lepton mass m_T



Discovery reach @ 3/ab: 850 GeV reference detector

ATLAS scope document CERN-LHCC-2015-020
Similar study bc CMS in CMS technical proposal

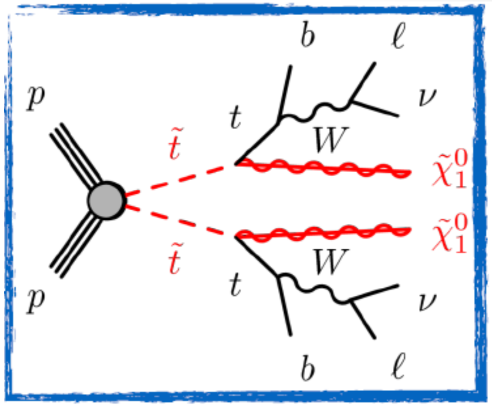
Direct stop pair production with compressed mass spectra

Compressed mass spectra

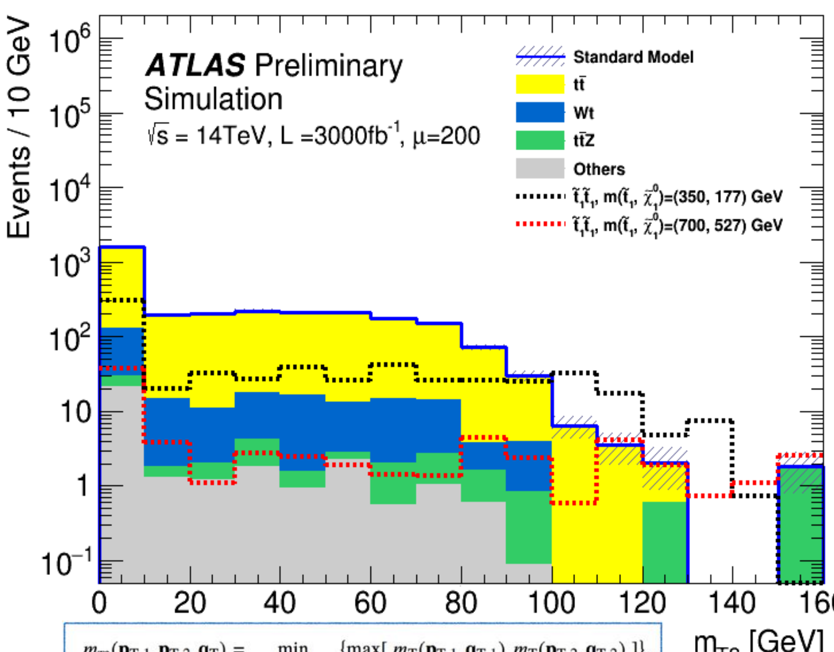
Scenario with low stop-neutralino mass difference

$$(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) \cong m_t$$

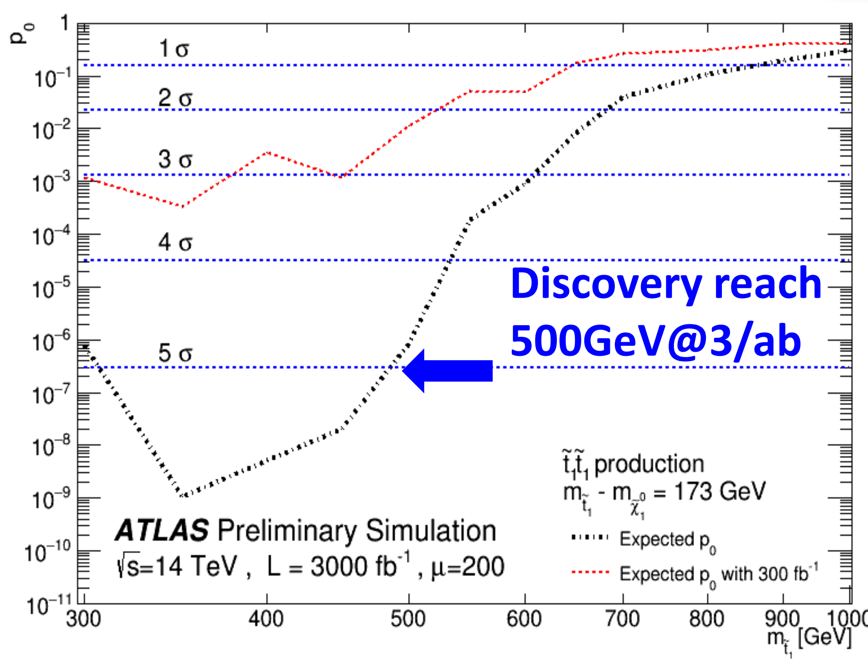
Project sensitivity of 2-lepton channel (needs luminosity), **key to study stop properties** (e.g. spin).



Signature: 2 leptons + 2 b-jets + MET

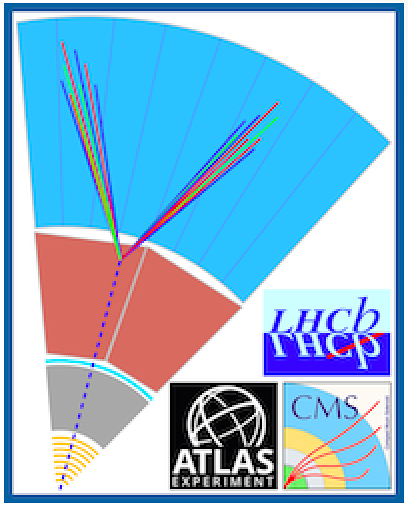


$$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{q}_T) = \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{q}_T} \{\max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2})\,]\},$$



ATL-PHYS-PUB-2016-022

Long-Lived Particles (LLP) and Special Signatures

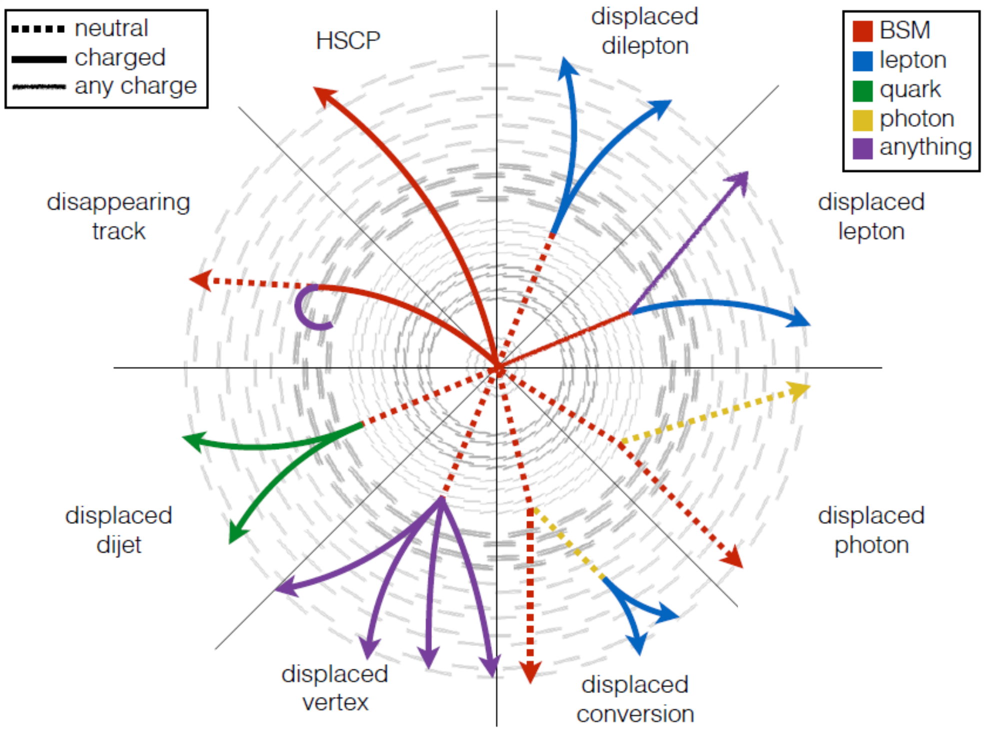


A new focus at the LHC, for present and future.

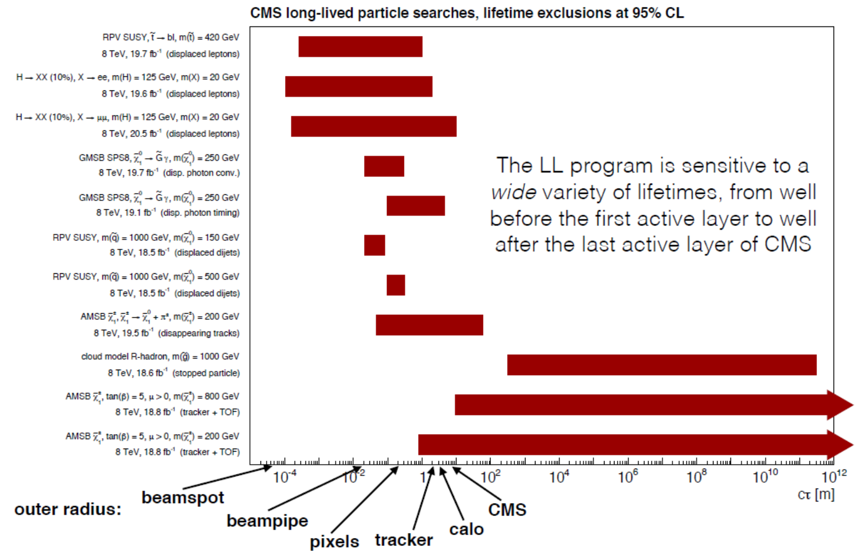
Signature driven searches, cover variety of SUSY and non-SUSY models and searches for BSM Higgs.

Need dedicated tools, to be prepared now for phase-II.

Special Signatures from LLP



Variety of dedicated techniques to cover whole range of lifetimes (cτ)



Issues and opportunities with LLP signatures:

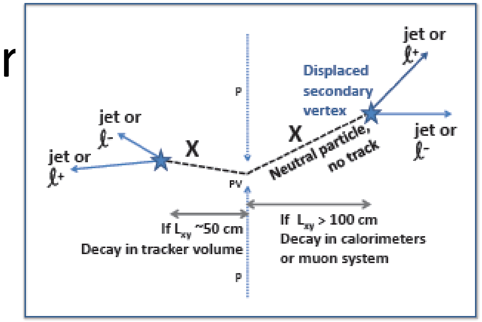
- **Non-standard** objects, **custom** trigger/reconstruction/simulation
- Need to maintain **dedicated** detector capabilities

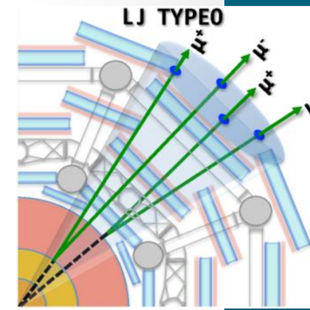
Potential gains from HL-LHC from high luminosity, track-trigger, fast timing, better directionality.

Displaced Muons from LLP

Long-lived neutral particle (X) decays after some cτ to displaced leptons or jets.

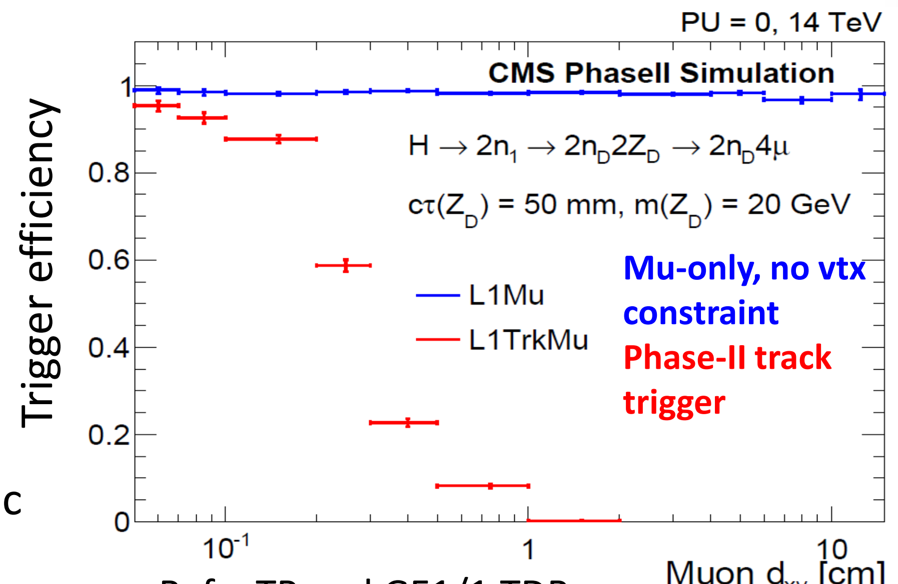
Example signature: **displaced muons** (possibly collimated)





ATLAS EXOT

Experimental challenge: trigger such displaced signatures (note: phase-II track triggers with vertex constraint).



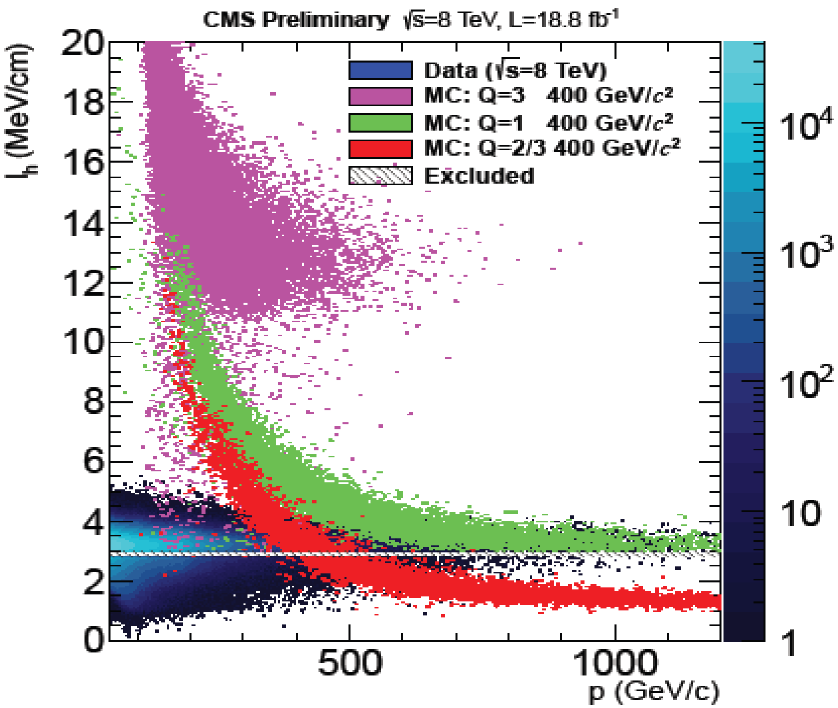
Ref = TP and GE1/1 TDR

Possible models: dark photons, inelastic thermal-relic DM, etc.

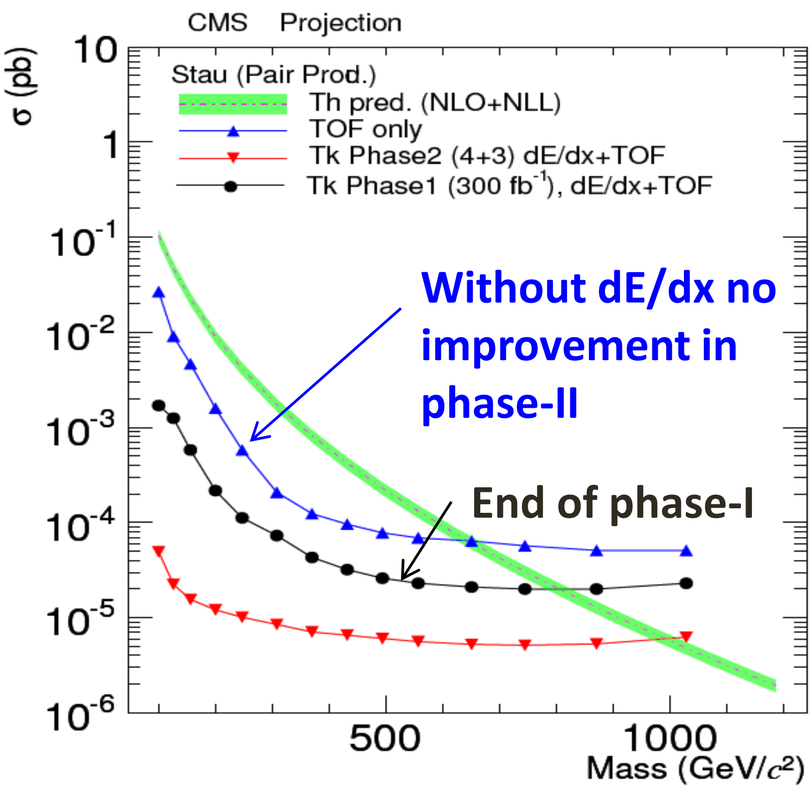
See also talk by Alexei Safonov on CMS muon performance & trigger

Impact of Detector Capabilities

Impact of dE/dx readout in CMS tracker



dE/dx information used in searches for heavy stable charged particles (HSCP), fractionally/multiple charged particles. But also to identify noise and background in „standard analyses“.



Physics studied demonstrated the need to keep dE/dx capability.

CMS TP and CMS-PAS-EXO-14-007

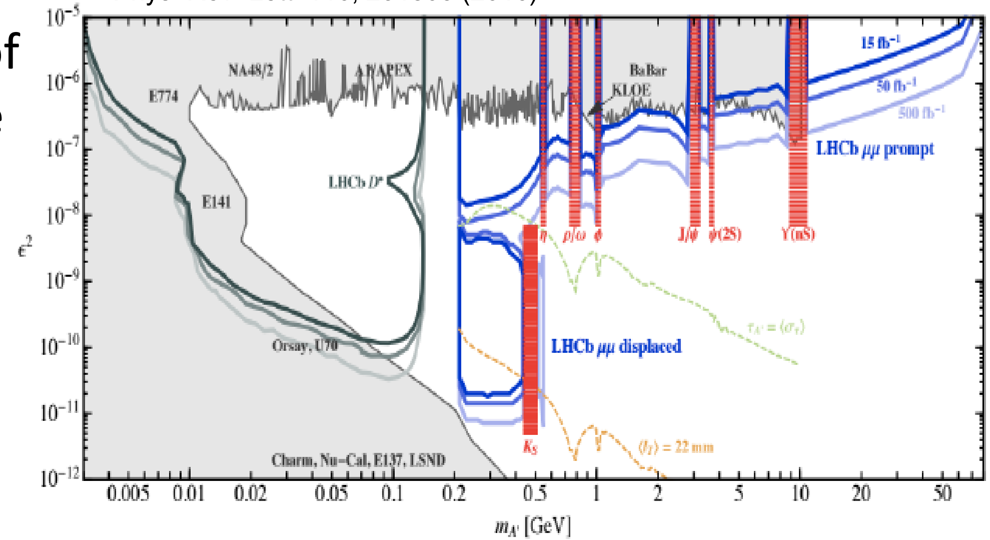
LHCb Contributions

More in LHCb talk by Niels Tuning later today

Many BSM theories predict some sort of hidden sector, weakly coupled to visible sector. Displaced lepton signature = smoking gun

e.g. dark photons (γ_D): Theory adds U'(1) whose massive bosons mix with SM, leads to A1, Z_D or γ_D along with other hidden particles which decay to LJ.

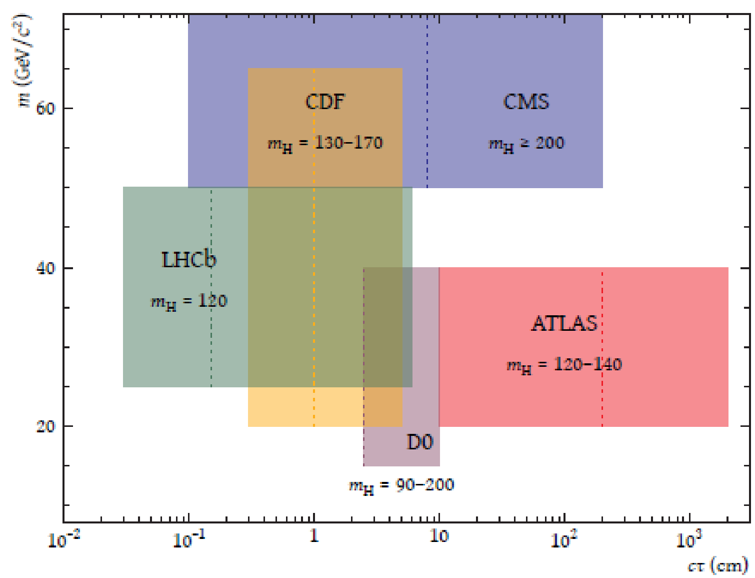
Phys. Rev. Lett. 116, 251803 (2016)



Important contributions from **LHCb** in particular for light particles. Profits from:

- Momentum resolution
- Good secondary vtx resolution due to lower pileup
- Very low p_T triggers
- Particle ID in RICH detectors

Eur. Phys. J. C75 (2015) 152



Summary

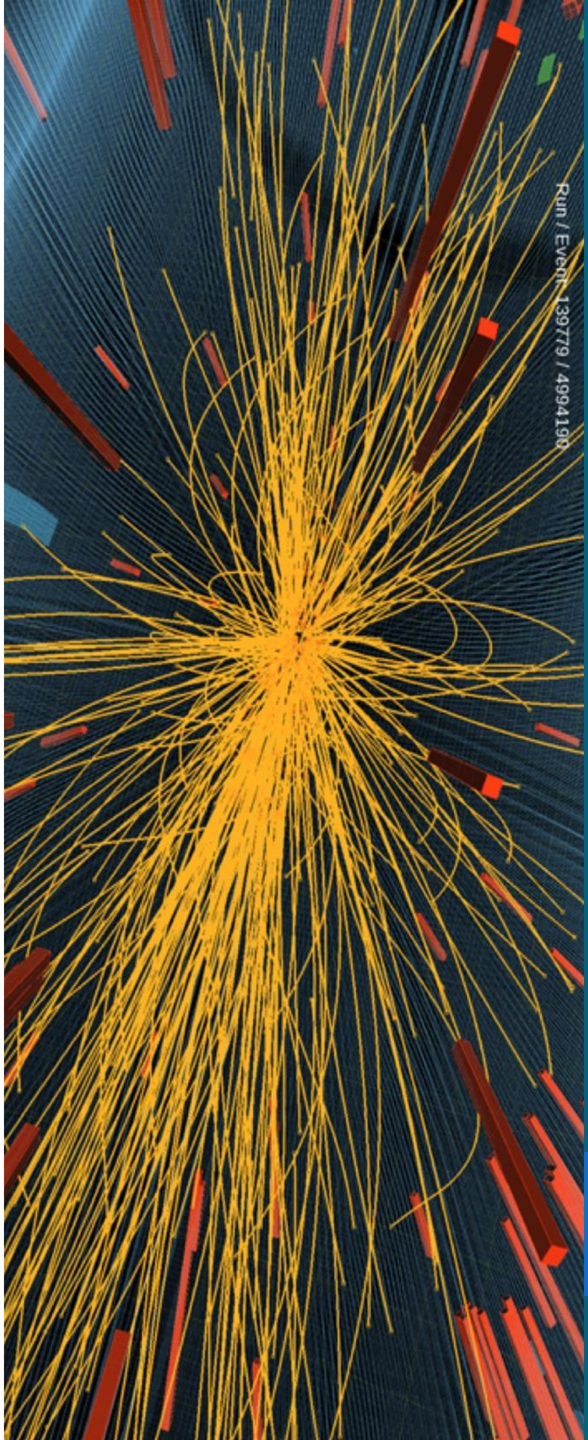
Rich BSM physics potential for HL-LHC

Several projections and full analyses for a variety of existing benchmark channels (heavy bosons, DM) reaching O(5-10 TeV).

New models of EW SUSY (direct stau production) considered for upgrade studies.

Developing new analysis strategies, e.g. displaced signatures for more model-independent analyses.

Reducing systematic uncertainties impacts sensitivity.

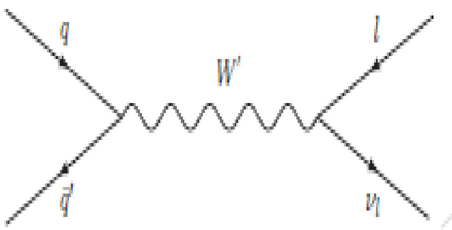


BACKUP MATERIAL

New Heavy Charged Particles
Projections from existing analyses

W´→eν

Goal: Benchmark analysis with maximum discovery sensitivity.



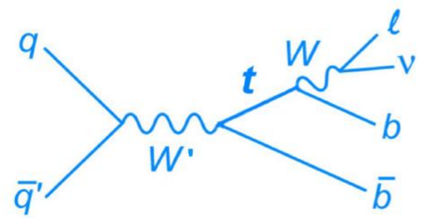
Discovery reach based on **DELPHES simulation**, systematics from run-2.

Experimental challenge: detector performance for high p_T leptons. TeV-muons may shower.

W´→tb

Goal: probe scenarios which cannot be studied with leptonic channels. Ex.: $m(\nu_R) > m(W')$ → forbidden for W´→lν

Final state b b {e/μ} ν



Projection of exclusion limit from 12.9/fb (13 TeV) to 3/ab

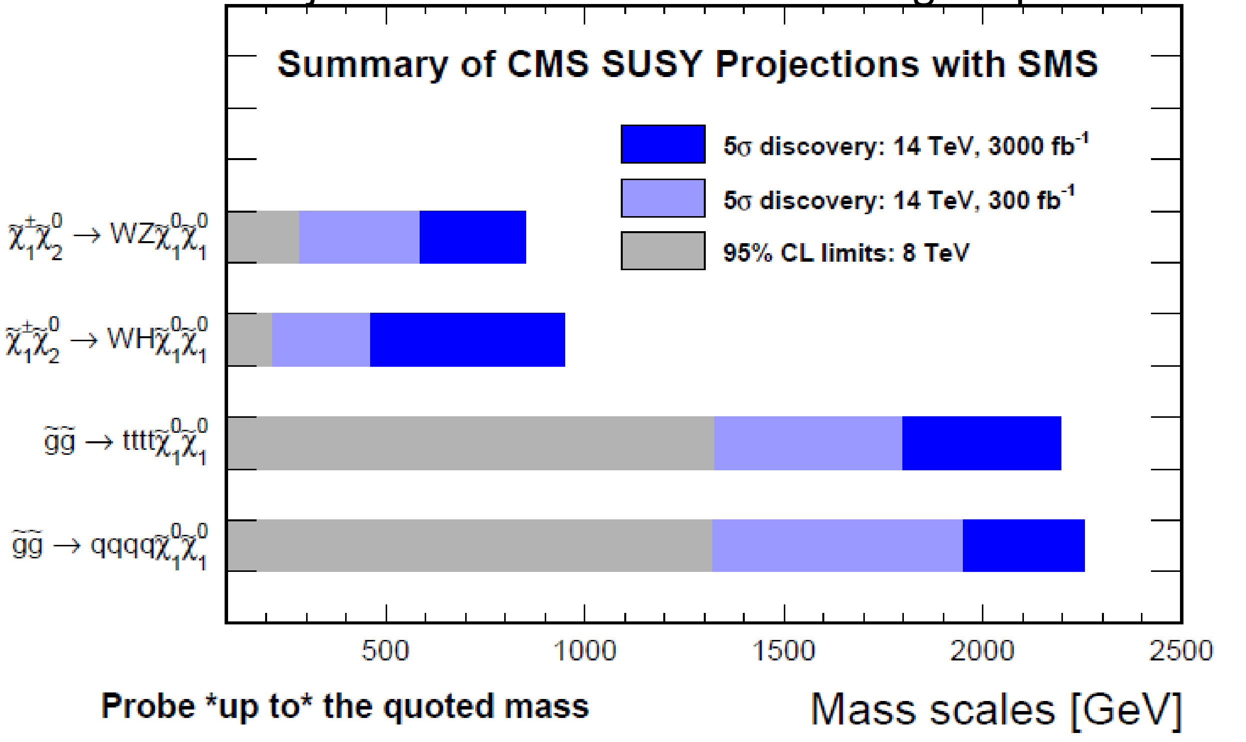
Experimental challenge: b-tagging in high pileup environment. Study impact of systematic uncertainties.

W'->eν from PAS-EXO-14-007.
Baseline analysis tb at 13 TeV B2G-15-004, B2G-16-017

Present searches often based on cascade decays of SUSY particles with many particles + MET (from LSP) in the final state. Exclusion limits reach O(TeV).

If discovery of new particle(s) → extensive measurements to **determine properties**, if indeed SUSY-partner of SM particle.
Understand the **SUSY breaking mechanism** = even more challenging.
Such program to extend for many years, because of the complexity of SUSY and associated decay processes.

Projections from 8 TeV results using simplified models



CMS-UpgradeTP_LHCC-P-008

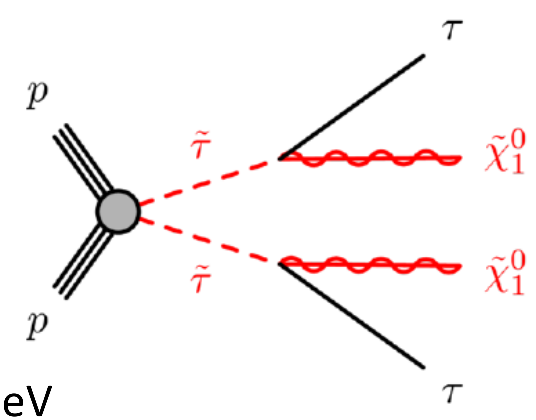
Direct Production of stau Pairs

Assume 100% BR to SM tau and LSP.

Signature:

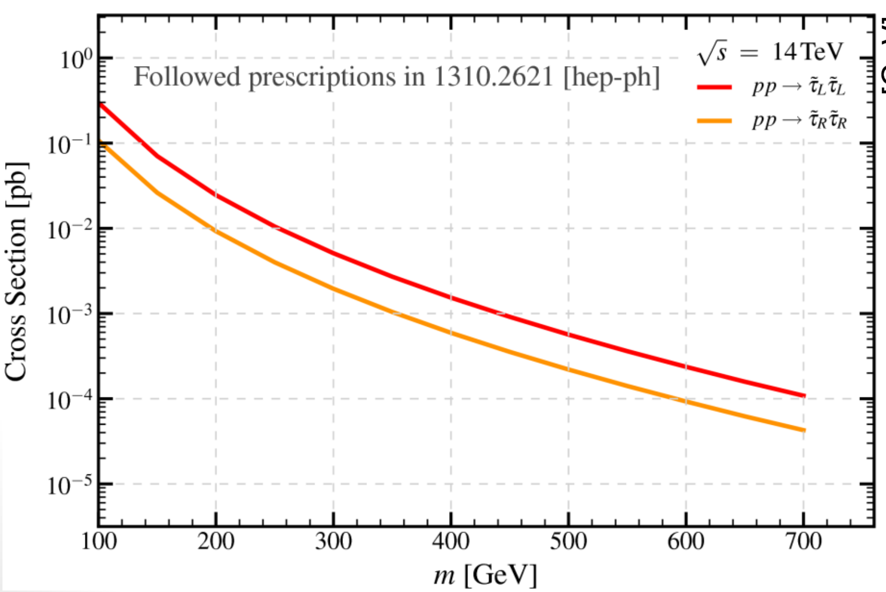
- 2 tau jets (hadronically decaying tau)
- Large MET (from $\tilde{\chi}_1^0$)

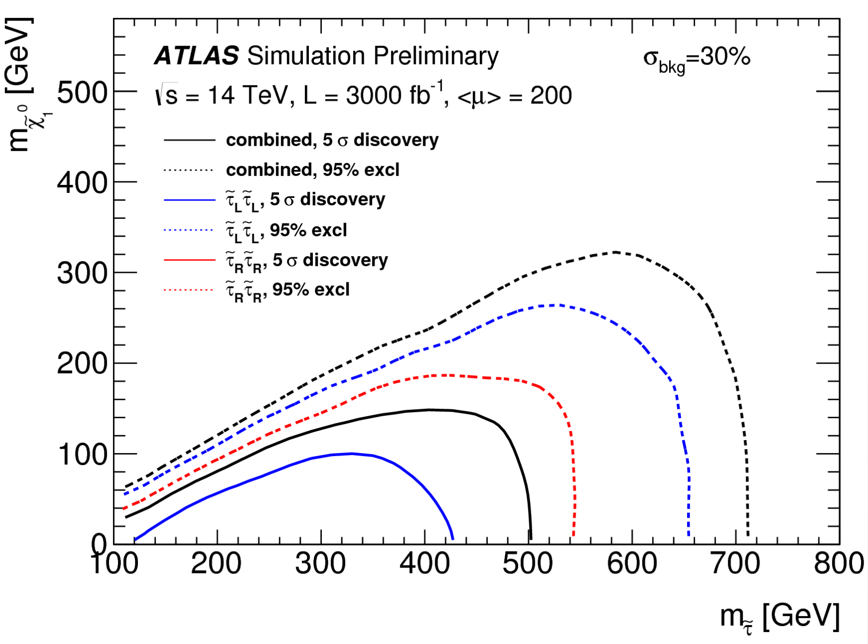
Main background: W+jets, ttbar



Selection: 2 OS taus, loose jet and Z-veto, MET>280 GeV

Define signal region (SR) in $m_T(\tau 1) + m_T(\tau 2)$





ATL-PHYS-PUB-2016-021

Exotic states of HH to bbbb

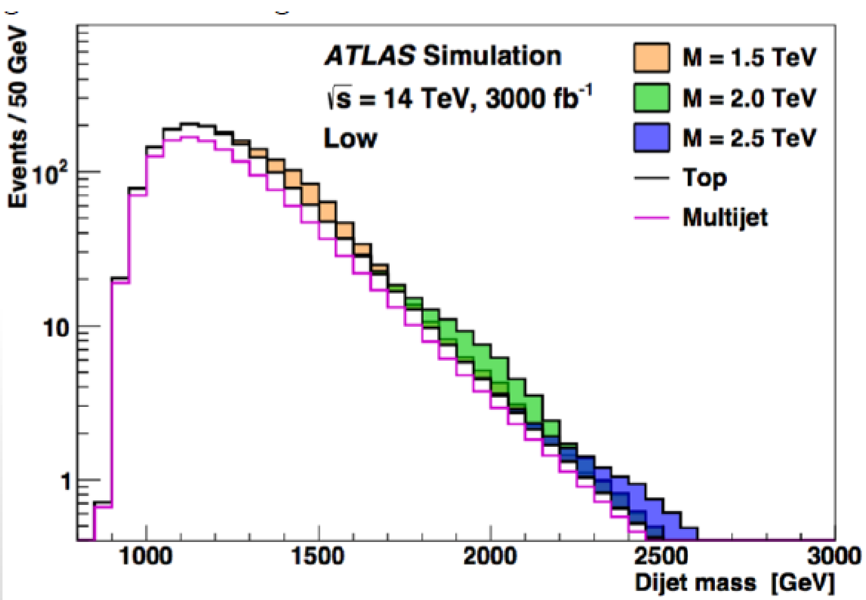
High-Mass Kaluza-Klein gravitons with each of the Higgs bosons decaying to $b\bar{b}$.

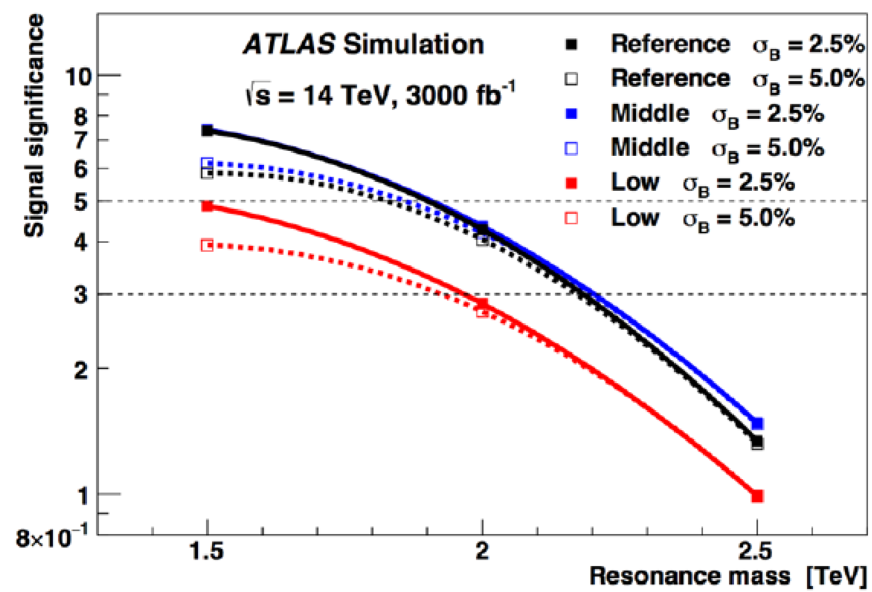
- Large Jet: anti-Kt R=1.0
- Track Jet: anti-Kt R=0.2. Used as proxy for "track jet" that are b-tagged.
- Trigger Jet anti-Kt R=0.4

Dominant background from QCD production.

Needs b-tagging → impact from upgrade scenario for medium masses

Technique similar to dijet analysis, looking for bump from a sharp resonance in spectrum. Sliding mass window around resonance mass for each signal mass point.





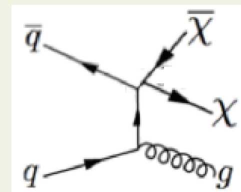
http://cds.cern.ch/record/2055248/files/LHCC-G-166.pdf

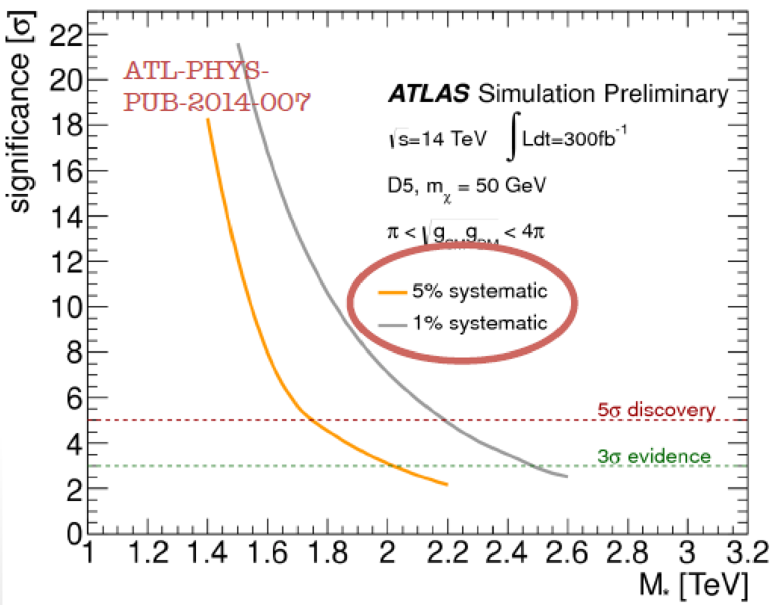
ATLAS DM study (EFT Approach)

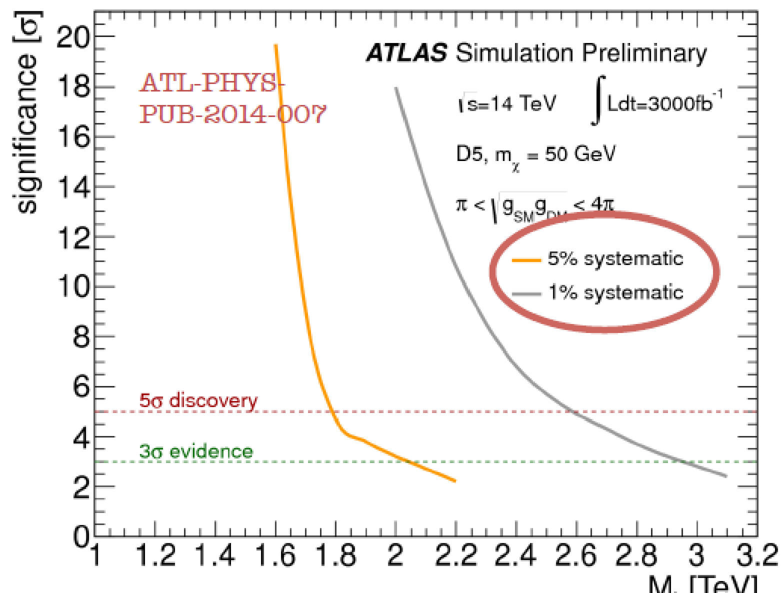
Dark Matter at the HL-LHC

Some old preliminary projections available, using EFT…

$$\mathcal{L}_{\text{Int}} = \frac{\overline{\chi}\gamma^{\mu}\chi\overline{q}\gamma^{\mu}q}{M_{*}^{2}}$$







What will the systematics be?

Shown by Matthew McCullough on Monday

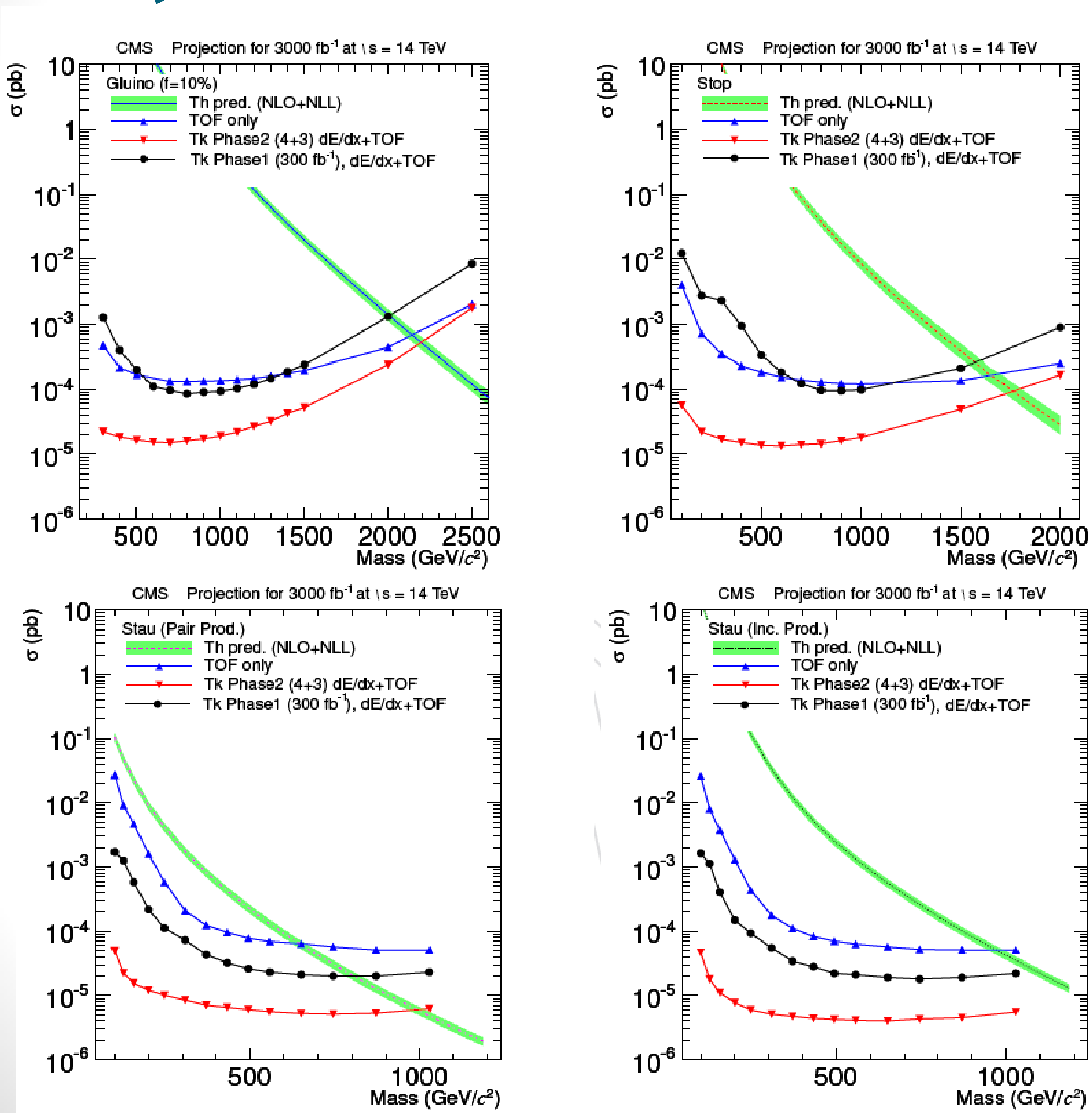
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2014-007/

Systematics on CMS Single VLQ

- Experimental:
- Electron/Muon identification/isolation: 1%
- B-tagging
  - 1% (2%) for b-jets (c-jets), pT independent
  - 2-10% mistagging, increasing with b-tagging purity
- Jet energy scale:
  - 1% for jets with pT >30 GeV for all eta
- Missing transverse momentum
  - Propagate from JES uncertainty
  - Component due to unclustered energy being studied
- Luminosity: 1.5%

- Modelling
- Renormalization and factorization scales
  - Scale by factor of ½ wrt results from LO generators (well-understood NLO generators)
- PDF
  - Scale by a factor of ½ wrt current measurements (more PDF constraints from LHC data, new sets)
- Top-quark pT
  - Scale by a factor of 1/3 wrt current measurements (precise differential cross section measurements, well-understood NLO generators, 2D differential NNLO k-factors)

Projections for Different Models



Assumptions for projection:

- Follow run-1 analysis in terms of selection and systematics.
- Bkgr, mostly instrumental, scales linearly with PU
- With 25ns lose ability to trigger on „late muons". 99% of particles $\beta<0.5$. Considered by random event rejections.

TP and CMS-PAS-EXO-14-007